Liquid Hydrocarbon Detonation Branching in a Pulse Detonation Engine

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Pulse detonation engines operate on a fill-detonate-exhaust cycle with thrust directly proportional to the cycle frequency. That is, a decrease in cycle time results in increased thrust. This paper shows that the detonate portion of the cycle can be shortened by using a branched detonation as the ignition source as opposed to a spark plug type of ignition. The combustion energy from a branched detonation allows ignition and deflagration-to-detonation transition to occur more quickly, shortening overall cycle time. Further, while detonation branching has been previously accomplished using gaseous hydrogen fuel, this paper reports the first application of detonation branching using liquid hydrocarbon fuel. For this application, a pressurized heating system was designed to vaporize the fuel and mix it with an airstream to stoichiometric conditions.

Nomenclature

c_p	=	constant-pressure specific heat
h	=	enthalpy
$\dot{m}$	=	mass flow rate
T	=	temperature

I.   Introduction

A pulse detonation engine (PDE) is comprised of thrust tubes that are closed at one end, filled with a combustible fuel-oxidizer mixture and ignited at the closed end. The resulting combustion develops into a detonation wave that causes a large mass flux and pressure differential to create thrust[1].

The detonation development is preceded by ignition and deflagration-to-detonation transition (DDT). Ignition begins with the introduction of a flame-causing external stimulus and ends with the development of a flame. DDT begins after ignition and ends with the development of a detonation, which is a moving shock wave coupled with a trailing combustion region.

The main goal of the research was to determine the time-savings for ignition and DDT using detonation branching, as compared to single-tube, single-spark ignition, in a PDE operating on a stoichiometric mixture of liquid hydrocarbon fuel and air. The use of detonation branching as an ignition source with hydrogen fuel has been demonstrated[2], as has the use of liquid hydrocarbon fuels in a PDE with spark ignition[3]. This paper reports the first attempt at combining the two concepts, i.e., using a branch detonation as an ignition source in a PDE running on liquid hydrocarbon fuel.

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Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE **2004**	2. REPORT TYPE	3. DATES COVERED **00-00-2004 to 00-00-2004**
4. TITLE AND SUBTITLE **Liquid Hydrocarbon Detonation Branching in a Pulse Detonation Engine**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory,Propulsion Directorate,Wright Patterson AFB,OH,45433**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT **see report**

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES **7**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

The first issue addressed is ignition and DDT time-savings obtained from using detonation branching as an ignition source. To accomplish this branching, a spark plug-ignited combustible mixture in a primary thrust tube ignites a fuel-air filled crossover tube leading to a secondary thrust also filled with a combustible mixture. A detonation forms in the crossover tube and travels into the second thrust tube where the combusting gases trailing the shock wave ignite the mixture[2].

The second issue addressed is efficient use of liquid hydrocarbon fuel in a branched PDE. To promote efficiency, a high-pressure fuel vaporization system was built to vaporize the liquid fuel and create a homogeneous fuel-air mixture upstream of the PDE. Vaporized fuel increases the PDE fuel efficiency by allowing it to operate with a stoichiometric fuel-air mixture.

II.   Materials and Method

A. Fuel

The choice of fuel was based on previous single-tube PDE research using a vaporization system where n-heptane had short DDT times and detonation speeds consistently at or above the Chapman-Jouguet (C-J) detonation velocity[3]. To avoid the coking that occurs when fuel is heated above 450 K[4], the oxygen content in the n-heptane was decreased to less than 1 ppm using nitrogen sparging.

B. Vaporization System

The role of the vaporization system was to convert liquid n-heptane to a completely gaseous state, allowing the PDE to use a stoichiometric fuel-air mixture. Figure 1 shows the heptane liquid-vapor dome to illustrate the state changes occurring in the vaporization system.

At point 1 in Fig. 1, liquid heptane is pressurized to 40 bar and heated to between 420 K and 500 K. Pressurizing above the critical pressure of 27 bar prevents boiling when the fuel is heated. Between points 1 and 2, the heptane is injected into a low pressure airstream in an adiabatic, constant enthalpy process in which the pressure drops to that of the airstream. At point 2, the fuel state lies inside the liquid-vapor dome. Between points 2 and 3, the heptane mixes with the heated airstream to form a completely gaseous mixture at point 3.

The initial fuel temperature of 420 K to 500 K used in the experiment is too low for immediate vaporization at the injection point. With a sufficiently hot airstream at the injection point, however, further vaporization occurs in the mixing tube leading to the PDE. The required

Figure 1.   Heptane liquid-vapor dome showing phase changes in the vaporization system.

air temperature for such vaporization can be obtained from an energy balance. Equation (1) shows the energy balance used to determine the air and fuel temperatures that would cause fuel in the liquid state to vaporize upon mixing with the airstream.

$$\dot{m}_{mixture}c_{p,mixture}T_{mixture} = \dot{m}_{air}c_{p,air}T_{air} + \dot{m}_{fuel}h_{fuel} \tag{1}$$

For various mixture pressures, the National Institute of Standards and Technology computer program SUPERTRAPP Version 3.1[5] computed $T_{mixture}$ for 0% to 100% vaporous stoichiometric heptane-air mixtures at equilibrium, shown in Fig. 2. The temperature at 100% vapor in Fig. 2 is $T_{mixture}$ in Eq. (1). For any pressure up to three bar, the mixture is purely vapor at mixture temperatures greater than or equal to 295 K.

For a mixture temperature of 295 K and pressure of three bar, Eq. 1 is plotted in Fig. 3. The air pressure used in the experiment was between 1.8 bar and 2.5 bar so the results are slightly conservative. In Fig. 3, the dashed line represents the fuel temperature required for immediate vaporization at the injection point and the solid line is from Eq. (1). The dot
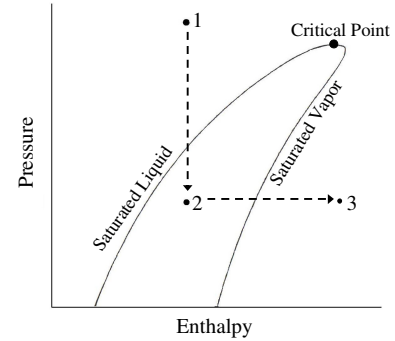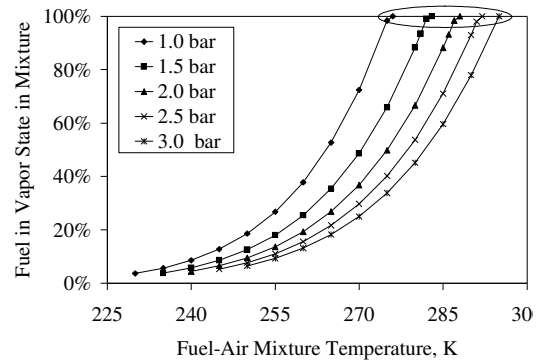

Figure 2. Percent of heptane in vapor state in a stoichiometric fuel-air mixture.

is the fuel and air temperatures just downstream of the injector in the PDE experiments.

Heptane at 40 bar and 514 K is vaporized upon injection, also known as flash vaporization, for a mixture pressure of 3.0 bar, which is the region to the right of the dashed line in Fig. 3. Heptane is entirely vapor in the stoichiometric fuel-air mixture in the region above the solid line in Fig. 3, as derived in Eq. (1). Thus the heptane in the experiment is not flash vaporized, but is in a completely vaporous state upon mixing with the airstream.

Figure 4 shows a schematic of the vaporization system and the PDE thrust tubes. The fuel, air and fuel-air mixture temperatures and pressures are noted at various locations in the system.

In the vaporization system, room temperature heptane was pressurized to 40 bar and fed into a 1.2 L reservoir in a furnace. The furnace heated the fuel in the reservoir to between 420 and 500 K. From the furnace, the fuel was injected into the 310 K and 1.8 to 2.5 bar airstream with three pressure atomizing nozzles. The fuel and air flow rates were controlled to ensure a stoichiometric mixture. All tubing, fittings and nozzles that would come in contact with heated fuel were Silcosteel® coated to prevent impurities in the metal from reacting with the hot fuel[6]. The coating was thin enough, on the order of hundreds of Angstroms[6], to cause a negligible decrease in fuel line and nozzle cross-sectional area.

When injected into the airstream, the fuel enthalpy remained constant during the pressure drop. To maintain constant enthalpy while part of the fuel energy was used to convert liquid fuel to the gaseous state, the fuel temperature decreased slightly. The lowest fuel temperature immediately downstream of the nozzles was 392 K at pressure of 1.8 bar.

The fuel and air flowed through 4.9 m of mixing length, completely vaporizing the fuel and forming a homogenous fuel-air mixture. The fuel-air mixture temperature was monitored in the mixing length at a point 0.16 m upstream of the manifold to ensure it did not fall below 310 K, giving a 5% safety margin above 295 K, the minimum temperature for an entirely vaporous heptane-air mixture at 3 bar according to Fig. 2.

From the mixing length, the fuel-air mixture flowed into the manifold where the pressure varied from 1.8 to 2.5 bar. Valves between the manifold and thrust tube heads controlled the flow rates into the heads. From the manifold, the vaporization system interfaced with the PDE and the fuel-air mixture was fed into the thrust tube heads.

Panzenhagen gives a further detailed description of the vaporization system[7].

Figure 3. Fuel and air temperature operating envelope, 3.0 bar airstream.
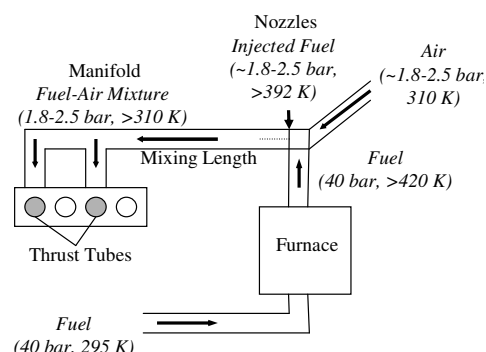
Figure 4. Vaporization system schematic with temperatures and pressures.

C. Pulse Detonation Engine

Schauer gives a detailed description of the PDE components and the control systems[8]. The PDE used valving from a General Motors Quad 4, Dual Overhead Cam cylinder head to control filling and exhausting of the thrust tubes[8]. Two ports allowed the fuel-air mixture to fill the thrust tubes during the fill part of the cycle and two different ports allowed air to enter the tubes to purge combustion products during the exhaust part of the cycle.

The PDE consisted of a 1.22 m thrust tube with a 5.5 cm inner diameter, a 1.22 m thrust tube with a 5.6 cm inner diameter and a 1.22 m crossover tube with a 1.7 cm inner diameter, shown in Fig. 5. To decrease DDT times by increasing hot spots and turbulence in the fuel-air mixture, each thrust tube had a 0.91 m Shelkin-like spiral installed adjacent to the head.

The ignition for first thrust tube was supplied by a spark plug that used capacitance discharge to create three 105-115 mJ
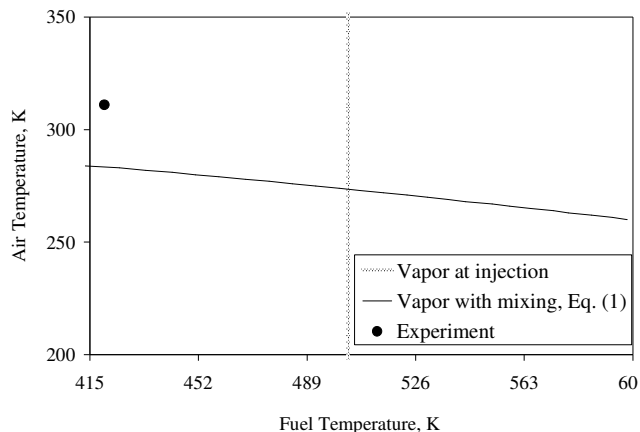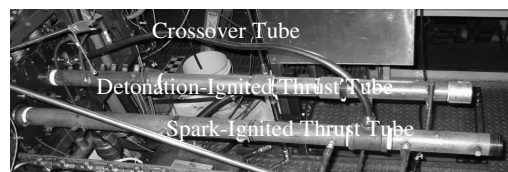
Figure 5. Thrust tubes and crossover tube.

sparks[3]. The second thrust tube ignition source was the detonation energy branched from the first tube and deposited into the second tube head via the crossover tube.

Pressure transducers and homemade ion sensors provided measurements for computing ignition and DDT times and detonation velocities and strengths. Model 102M232 pressure transducers from PCB Piezotronics were located in the thrust tube heads to capture pressure rises associated with ignition and detonation development.

The ion sensors were fabricated from NGK spark plugs, model C-9E, part 7499. As combustion waves passed the transducers they registered voltage drops that were recorded by LabVIEW[TM] software. Dividing the distance between two ion sensors by the combustion wave time gave the average wave velocity at the midpoint between the sensors.

In this research, the PDE had a 20 Hz cycle frequency. The valving in the detonation-ignited thrust tube lagged the valving in the spark-ignited thrust tube by one-quarter of a cycle, or 12.5 ms. The timelines for the two thrust tube cycles at 20 Hz are in Fig. 6.

Sparking delay is defined as the time from the moment the valves close at the end

Figure 6. Cycle timelines for both thrust tubes at 20 Hz.

of the fill part of the cycle, signaling the beginning of the detonate part of the cycle, to the moment the sparks are deposited in the head of the spark-ignited thrust tube. Without a sparking delay, the primary tube detonation would branch over to second tube in the fill part of the cycle, causing a backfire. With an 8 ms sparking delay this was avoided.

D. Detonation Velocity

According to the computer program for Calculation of Complex Chemical Equilibrium Compositions and Applications developed by the NASA Lewis Research Center[9], the C-J detonation velocity for a stoichiometric heptane-air mixture is 1,794 m/s. In this research, any combustion wave traveling at or above the C-J detonation velocity is considered a detonation.

III. Results and Analysis

A. Detonation Development

One important parameter is the location of the detonation point in each tube, i.e., the point where the combustion wave reaches detonation velocity. To determine the detonation point, each thrust tube was lined with ion sensors and the PDE was fired normally, with the first tube using spark ignition and the second tube using detonation ignition. Ion sensor readings were used to calculate combustion wave velocities.

For the spark-ignited thrust tube, ion sensor readings at 0.09, 0.24, 0.50, 0.71, 0.91, 1.08 and 1.23 m were used to calculate combustion wave velocities at 0.17, 0.37, 0.60, 0.81, 1.00 and 1.16 m, the midpoints between sensors. At a 20 Hz cycle frequency, data was taken for 0.8 s, capturing 16 cycles. Figure 7 shows the wave speed at each velocity measuring point for each cycle. The horizontal line in the plot indicates C-J detonation velocity, 1,794 m/s. The thrust tube diagram at the top of Fig. 7 follows the x-axis scale; diagonal lines indicate the Shelkin-like spiral and marks on top of the tube indicate ion sensors.

As seen in Fig. 7, the combustion wave speed tended to increase through the spiral. The peak at 1.0 m indicated a superdetonation wave. The detonation point was the first point where the average wave speed was greater than or equal to the C-J detonation velocity. For the spark-ignited thrust tube, the detonation point was 1.00 m with an average wave speed of 2,375 m/s.

The combustion wave velocity was expected to increase until it reached C-J detonation velocity. In Fig. 7, the average velocity decreased slightly between
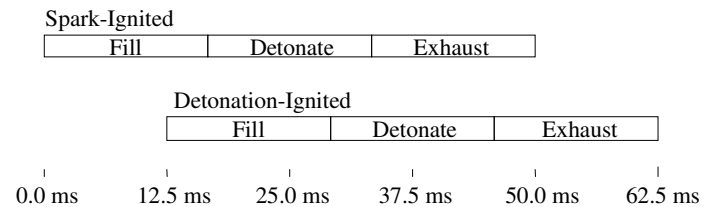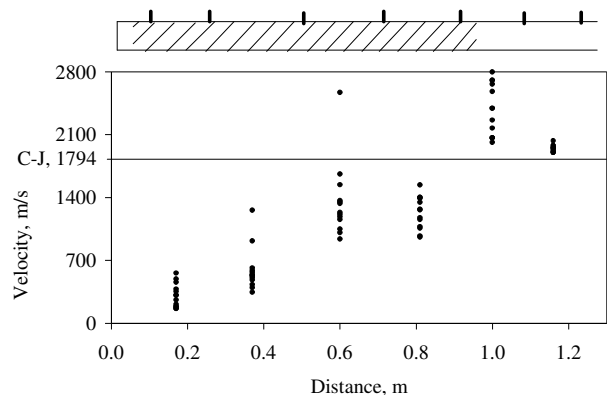

Figure 7. Spark-ignited thrust tube and corresponding wave speeds.

0.60 and 0.81 m. The velocity also decreased between 1.00 and 1.16 m as detonation wave speed decreases to C-J detonation velocity after spiking with the superdetonation wave.

The detonation point was also determined for the detonation-ignited thrust tube. Readings from ion sensors at 0.08, 0.19, 0.30, 0.43, 0.58, 0.75 and 0.90 m were used to calculate average combustion wave velocities at 0.13, 0.25, 0.37, 0.51, 0.67 and 0.83 m, the midpoints between the sensors. The cycle frequency was 20 Hz and data was taken for 0.8 s, capturing 16 cycles. Figure 8 shows the velocities with the corresponding thrust tube diagram above the plot.

As seen in Fig. 8, the wave speeds tended to increase through the spiral. The detonation point was 0.83 m with an average wave speed of 1,940 m/s. This detonation point was approximately 0.17 m shorter than the spark-ignited tube detonation point, an indication that detonation ignition is more efficient than spark ignition.
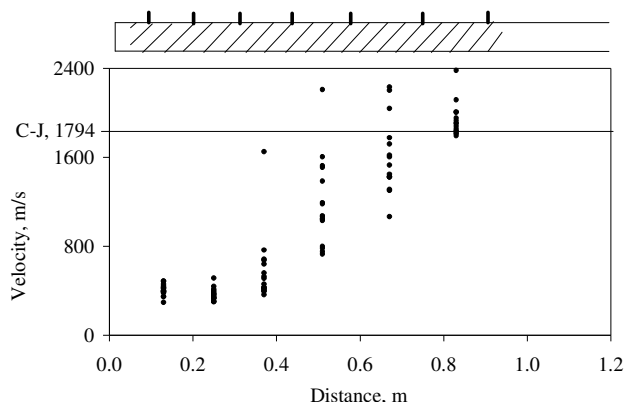

Figure 8. Detonation-ignited thrust tube and corresponding wave speeds.

B. Detonation Branching Verification

The crossover tube was located at 1.00 m, the detonation point on the spark-ignited thrust tube. The average combustion wave velocity at this point was 2,375 m/s, well above the C-J detonation velocity of 1,794 m/s. This indicated that a strong detonation was branched into the crossover tube.

To ensure a detonation arrived in the detonation-ignited tube, the wave speed was measured in the crossover tube just upstream of the detonation-ignited tube head. Ion sensors at 0.20 and 0.30 m from the head of the detonation-ignited tube head gave the velocity at 0.25 m. The cycle frequency was 20 Hz and data was taken for 0.8 s, resulting in 16 velocity measurements. The average wave speed was 1,634 m/s, 9% below C-J detonation velocity but an order of magnitude above that of a deflagration.

C. Ignition Time-Savings

In the spark-ignited thrust tube, ignition delay was the time from the spark being deposited in the head until the pressure transducer in the head indicated a pressure rise associated with combustion. Due to the sparking delay, sparks were deposited in the head 8 ms into the detonate part of the cycle. Ignition occurs when the head pressure trace slope could be differentiated from the noise in the system.

Figure 9 shows the pressure trace for the spark-ignited head, indicating when the spark was input in the head and when combustion occurred. In the figure, zero seconds begins the detonate part of the cycle in the spark-ignited thrust tube. At a 20 Hz cycle frequency, data was taken for 0.8 s, resulting in 16 data points. The average ignition delay, the time between the spark and ignition, was 5.632 ±0.004 ms.

In the detonation-ignited thrust tube, ignition delay was the time between the branched detonation arriving in the head and the pressure increase indicating combustion. Figure 10 shows the detonation-ignited thrust tube head pressure with 0.0125 s indicating the beginning of the detonate part of the cycle in that tube. The sharp pressure rise at 17.0 ms was the detonation entering the head. The

Figure 9. Spark-ignited tube head pressure trace.

detonation created a pressure and temperature rise that cause almost immediate ignition. The average ignition delay in the detonation-ignited thrust tube was 0.189 ±0.004 ms.
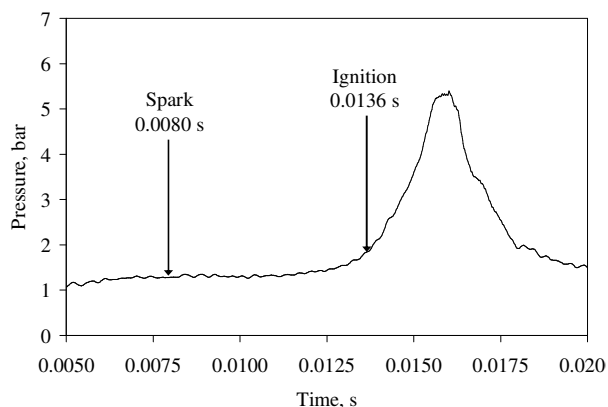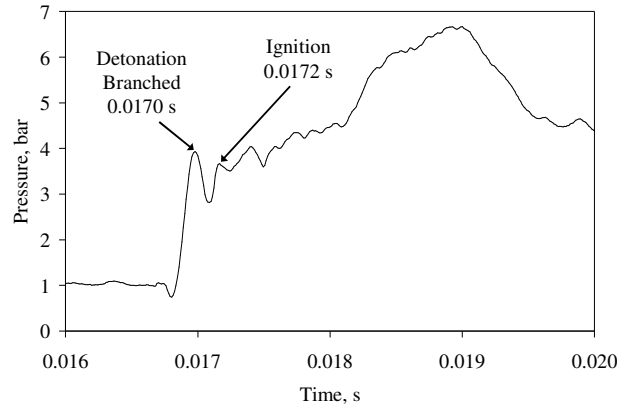
Figure 10. Detonation-ignited tube head pressure trace.

D. DDT Time-Savings

DDT time was the time between ignition and the combustion wave passing the detonation point. For the spark-ignited tube, an ion sensor at 0.91 m approximated the detonation point of 1.00 m. For the detonation-ignited tube, the ion sensor was at 0.98 m, 0.15 m beyond the detonation point. To account for the 0.15 m between the detonation point and the ion sensor, 80 μs, the time for a C-J detonation wave to travel 0.15 m, was subtracted from the voltage spike time to calculate DDT times.

Figure 11 shows the spark-ignited thrust tube ignition point, indicated on the head pressure trace, and the voltage drop from the combustion wave passing the 0.91 m ion sensor.   In the figure, zero seconds was the beginning of the detonate part of the cycle in the spark-ignited thrust tube.   DDT time was the time between ignition and the voltage drop. The average DDT time was 2.364±0.001 ms.

Figure 12 shows the detonation-ignited thrust tube ignition point, from Fig. 10, and the voltage drop from the combustion wave passing the 0.98 m ion sensor.   In the figure, zero seconds was the beginning of the detonate part of the cycle in the spark-ignited thrust tube.   DDT time was the time between ignition and the voltage drop minus 80 μs. The average DDT time was 1.031±0.001 ms.
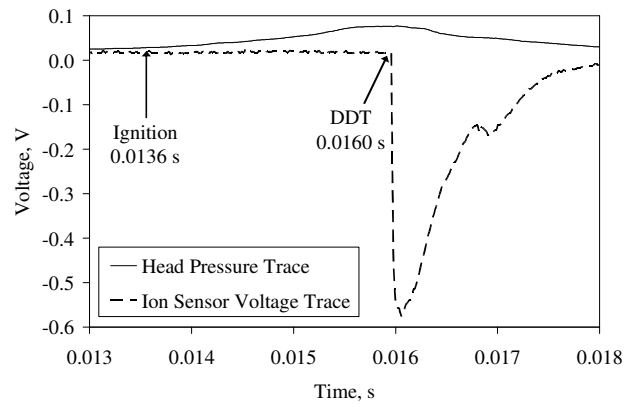

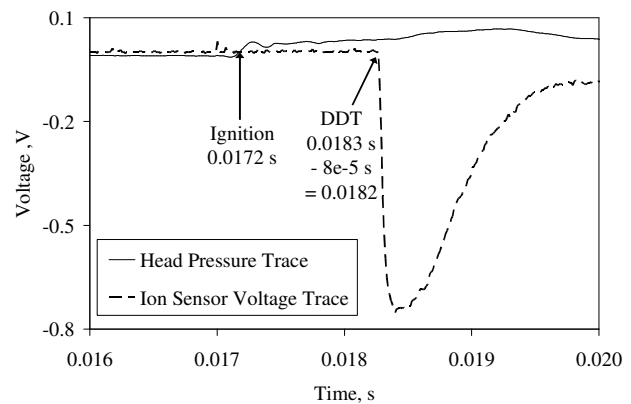**Figure 11.   Ion sensor voltage trace showing ignition and DDT points for the spark-ignited thrust tube.**

Figure 12.   Ion sensor voltage trace showing ignition and DDT points for the detonation-ignited thrust tube.

IV. Conclusions

Branched detonation ignition is feasible for a stoichiometric heptane-air mixture. Such ignition via detonation energy is more efficient than spark ignition as evidenced by the shorter distance to obtain C-J wave speed: 0.83 m compared to 1.0 m for the spark ignition tube. Detonation-branching ignition results in a cycle time-savings over spark ignition, shown in Table 1. In the PDE configuration in this research, the total time of ignition and DDT was reduced by 85% by using detonation branching.

Table 1. Ignition and DDT time comparison.

	Spark-Ignited	Detonation-Ignited
Ignition [ms]	5.632 ±0.004	0.189 ±0.004
DDT [ms]	2.364±0.001	1.031±0.001

Acknowledgments

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